Development of a simple analytical model to quantify the PV module cost premium associated with module efficiency and cell technology

Moon Hee Kang [a,*], Ajeet Rohatgi [a,b], Alan Ristow [c]

[a] University Center of Excellence for Photovoltaics Research and Education, School of Electrical and Computer Engineering, Georgia Institute of Technology, 777 Atlantic Drive, Atlanta, GA 30332, USA
[b] Founder and CTO, Suniva Inc., 5775 Peachtree Industrial Blvd, Norcross, GA 30092, USA
[c] Photovoltech NV, Industrial Area West Grijpen, Grijpenlaan 18, 3300 Tienen, Belgium

ARTICLE INFO

ABSTRACT

A simple analytical model and corresponding analytical equations were developed to rapidly determine the module cost premium associated with module efficiency, temperature coefficient (γ), irradiance weighted operating cell temperature (T_{iwoct}), and balance of system (BOS) cost. The model provides guidelines for selecting the most appropriate photovoltaic (PV) module for a given application and establishes the price of various modules without affecting the LCOE. Analytical calculations in this paper were verified with the more elaborate PV system analysis program called the System Advisor Model (SAM) from National Renewable Energy Laboratory (NREL). For example, it is shown that 16% efficient \$1/W module with area-related BOS cost=\$1/W, total BOS cost=\$2/W, $\gamma = -0.45\%/^\circ C$, and $T_{iwoct}=47.3\,^\circ C$ is equivalent to a 20% \$1.20/W module if BOS, γ, and T_{iwoct} remain the same. This corresponds to a premium of \$0.20/W due to a higher efficiency. If the 20% efficient module has γ of $-0.40\%/^\circ C$ instead of $-0.45\%/^\circ C$, then it will produce more energy, so the module cost can be increased to \$1.24/W without altering levelized cost of electricity (LCOE). This corresponds to an additional price premium of \$0.04/W due to γ. If T_{iwoct} is reduced to 42.3 $^\circ C$ instead of 47.3 $^\circ C$ by cooling or changing location, then another \$0.06/W premium can be added on the module cost.

© 2014 Elsevier Ltd. All rights reserved.

Contents

1. Introduction

PV industry has experienced a remarkable growth due to rising interest in green energy, PV cost reduction, and favorable policies [1–5]. Various technologies are being investigated with the

objective of increasing cell efficiency and reducing the cost to attain grid parity. Cost reduction can come from either module or BOS cost. Since total BOS cost is a function of module efficiency due to area-related BOS components, module cost needs to be adjusted to account for the difference in BOS cost in order to maintain the same installed system cost or LCOE [6]. In this paper, a simple model with analytical equations is developed to immediately determine the price for different modules with varying efficiencies, cell parameters

or equivalent technologies, operating conditions, and BOS costs. SAM type program which is widely used for LCOE calculations does not provide option to determine the price of PV modules depending on its performance but has to change module cost over and over until its LCOE matches with reference system.

Model accounts for different cell technologies and operating conditions by allowing the change in temperature coefficient (γ) for efficiency degradation, module efficiency, and T_{iwoct} simultaneously. Calculations were performed to compare promising cell technologies, namely crystalline Si (c-Si), CIGS, CdTe, and amorphous Si (a-Si). Since BOS cost can be different in different regions of the world and may decrease in the future [1,2], calculations are also performed to quantify the impact of BOS cost on module cost premium using the analytical equations.

2. Analytic modeling

2.1. Derivation of the analytical equations to assess the module cost

This section describes the analytical model to quantify the equivalent cost of any module relative to a reference module so that LCOE remains unchanged. Cost of an installed PV system consists of module cost (C_{Mod}), inverter cost (C_{Inv}), area-related BOS cost (C_{Area}), and fixed or indirect BOS cost (C_{Fix}) [6]. Sum of all cost components, except the module, is often referred to as total BOS cost (C_{BOS}).

$$System\ Cost = C_{Mod} + C_{Inv} + C_{Area} + C_{Fix} = C_{Mod} + C_{BOS}. \quad (1)$$

Area-related BOS cost consists of wiring/mounting hardware and installation labor cost, which is linear with respect to number of modules or system area. Therefore, area-related BOS cost is inversely proportional to module efficiency because higher efficiency module requires fewer modules for a given size system (kW). Fixed or indirect cost includes engineering, design, site preparation, grid connection, management, sales tax, and installer margin, which is independent of system area or module efficiency. Similarly inverter cost is independent of module efficiency because it is dictated by system size.

When we determine the cost of a new module, installed system cost from the new module should be equal to a reference module (assuming same γ and T_{iwoct}). This is because same installed system cost will result same LCOE when γ and T_{iwoct} are the same. If we compare modules from the same material and technology (same γ and T_{iwoct}) but different efficiencies, then the module costs should be adjusted to provide same installed system cost or LCOE. Since C_{Area} depends on module efficiency (η), cost of a new module in this case must be adjusted simply by an amount equal to the difference in C_{Area}. Therefore, module cost (C_{Mod}) of different efficiency modules can be expressed as

$$C_{Mod} = C_{Mod\_ref} + C_{Area\_ref}\left(\frac{\eta - \eta_{ref}}{\eta}\right), \quad (2)$$

where C_{Area_ref}, η_{ref}, and C_{Mod_ref} are area-related BOS cost, efficiency, and cost of the reference module, respectively.

Analytical equation (2) only accounts for the difference in module efficiency, but does not account for the difference in γ and T_{iwoct}, which dictates the operating temperature induced efficiency degradation [6–9]. This is important when cells or modules from different semiconductor materials are used, which can have different values for γ (Table 1). Difference in T_{iwoct} can occur from change in climate or location, mounting strategy, and module structure [6,10]. For example, polymer/thin film/steel structure is used for thin film modules (CIGS, CdTe, and a-Si) while glass/cell/polymer structure is used for c-Si module. Modules can run also cooler if mounted for better air flow or

Table 1
Temperature coefficient (γ) and T_{iwoct} for four commercially important terrestrial PV materials. T_{iwoct} was computed for south-facing open-rack-mounted PV arrays at latitude tilt on Phoenix, AZ (33.4°) and Boston, MA (42.4°).

Material	Bandgap (eV)	γ (%/°C)	T_{iwoct} (°C) at Phoenix	T_{iwoct} (°C) at Boston
Crystalline silicon (c-Si)	1.12	−0.45	47.3	27.3
Copper indium gallium diselenide (CIGS)	1.04–1.68	−0.34	45.1	24.9
Cadmium telluride (CdTe)	1.44	−0.25	45.1	24.9
Amorphous silicon (a-Si)	1.4–1–1.9	−0.20	45.1	24.9

have some passive cooling features. Therefore, in the following section, we have modified analytical equations to account for the impact of γ and T_{iwoct} on module cost. For numerical method how to calculate T_{iwoct} and more T_{iwoct} data for specific locations, one can check reference [6].

Since percentage of efficiency loss is defined as $\gamma\,(T_{iwoct} - 25\ °C)$ where γ is a negative number expressed as %/°C, a module with lower absolute value of γ will lose less power and produce more energy. This extra energy (W) can be monetized in terms of module cost ($/W). For example, when specific module produces double energy than reference module it can charge double price than reference module to the customer. To account this, we defined a compensation factor 'β', which accounts for the difference in efficiency production of the new module with respect to the reference module and is described as

$$\beta = \frac{[100\% + \gamma(T_{iwoct} - 25\ °C)]}{[100\% + \gamma_{ref}(T_{iwoct\_ref} - 25\ °C)]}. \quad (3)$$

Since the module with lower γ will provide more energy even though system size is the same, the installed system costs of the two systems need to be different for the same LCOE. This is done by multiplying the reference module system cost by 'β' and equating it to the system cost with the new module:

$$New\ System\ Cost = \beta \cdot (C_{Mod\_ref} + C_{Inv\_ref} + C_{Fix\_ref} + C_{Area\_ref})$$

$$C_{Mod} + C_{Inv} + C_{Fix} + C_{Area} = \beta \cdot (C_{Mod\_ref} + C_{Inv\_ref} + C_{Fix\_ref} + C_{Area\_ref}) \quad (4)$$

where

$$C_{Inv} = C_{Inv\_ref}, C_{Fix} = C_{Fix\_ref}, C_{Area} = C_{Area\_ref}\frac{\eta_{ref}}{\eta}$$

$$C_{Mod} = \beta \cdot C_{Mod\_ref} + (\beta - 1) \cdot (C_{Inv\_ref} + C_{Fix\_ref}) + C_{Area\_ref} \cdot \left(\beta - \frac{\eta_{ref}}{\eta}\right). \quad (5)$$

3. Results and discussions

3.1. Applications of the analytical equations to establish the cost of modules with different efficiency and cell technology for the same LCOE

For equivalent module cost calculations, system cost and parameters for a reference system need to be defined. Table 2 lists the reference system costs and parameters used for calculations. System cost and parameters come from current industry standard and most commonly seen in the market.

3.1.1. Determination of the Si module cost as a function of module efficiency for the same LCOE

Using the analytical equation (2), calculations were performed to quantify the cost of different efficiency c-Si modules, which results in the same installed system cost and LCOE. In this

example, γ and T_{iwoct} were kept constant and only the efficiency was varied. Calculations were performed for various area-related BOS costs in the range of \$0.25–2/W using a 16% efficient reference Si module. Note that BOS cost can be very different in different regions of the world and may decrease further in the

Table 2
Reference inputs used for module cost calculations.

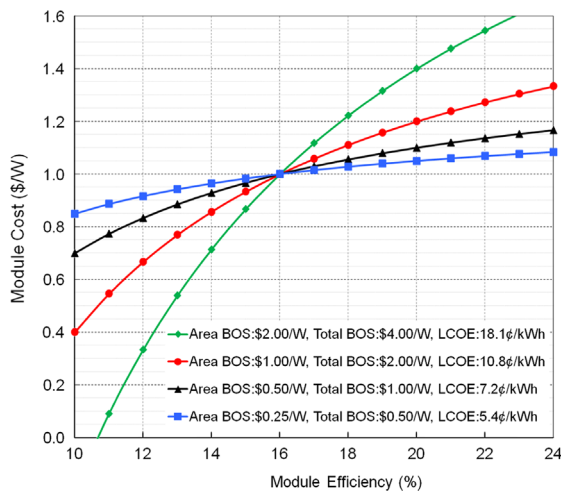| Item	Value
Module cost (\$/W)	1.00
Module efficiency (%)	16
γ (%/°C)	−0.45
T_{iwoct} (°C)	47.3
C_{Area} (\$/W)	0.25–2.00
$C_{Inv} + C_{Fix}$ (\$/W)	0.25–2.00
C_{BOS} (\$/W)	0.50–4–4.00
Installed system cost (\$/W)	1.50–5.00–5

Fig. 1. c-Si module costs as a function of module efficiency for various BOS costs with \$1/W 16% efficient c-Si reference module. Each curve represents a constant LCOE. LCOE was calculated with an assumption of weighted average cost of capital (WACC)=7.7% without ITC in Phoenix.
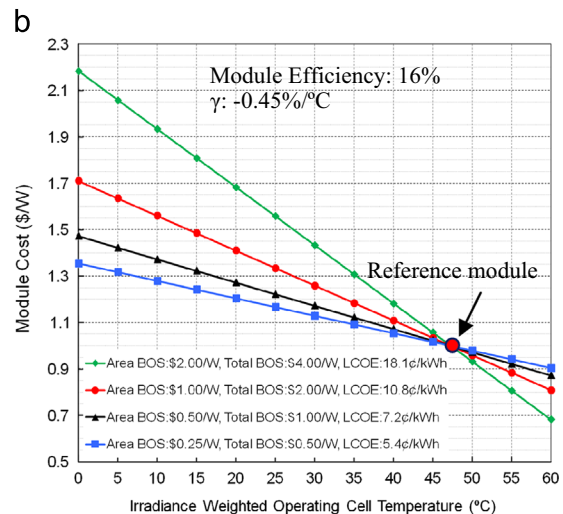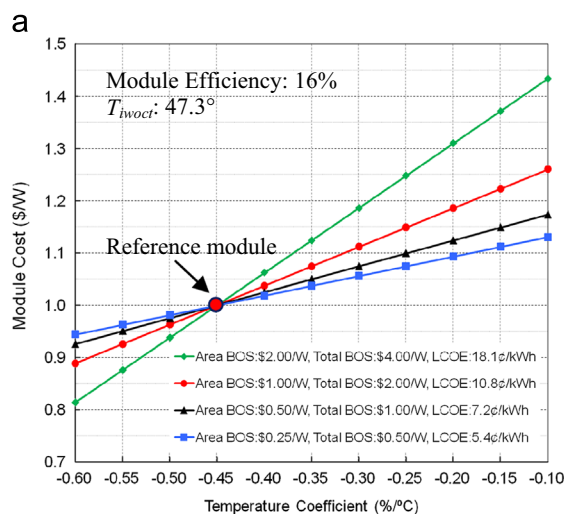
future. Recall that area-related BOS cost varies with efficiency ($C_{Area} = C_{Area\_ref}(\eta_{ref}/\eta)$). Since in this example γ and T_{iwoct} are the same, each curve in the following figures corresponds to a same system cost. Fig. 1 shows that as area-related BOS cost decreases, the cost premium (additional cost for high efficiency can get) for higher efficiency modules decreases. This is because slope of Fig. 1 is ($(dC_{Mod}/d\eta) = C_{Area\_ref}(\eta_{ref}/\eta^2)$). Note that η_{ref} can also change the slope of Fig. 1. For example, a 16% mono-Si module can have premium of \$0.29/W over a 14% mc-Si module when area-related BOS cost is \$2/W. This premium decreases to \$0.07/W when area-related BOS cost drops to \$0.5/W. Thus, if a 14% module sells for \$0.7/W, the 16% efficient module can be sold for \$0.99/W if the area-related BOS cost is \$2/W and \$0.77/W for area-related BOS cost of \$0.5/W.

3.1.2. Determination of equivalent cost of modules from different materials and cell technologies (c-Si, CIGS, CdTe, and a-Si)

In this section, we used analytical equation (5) to establish cost of modules made from different materials and technologies (different γ and T_{iwoct}) while maintaining the same LCOE. Results are plotted in Fig. 2 for various BOS conditions while module efficiency was kept constant at 16%. Calculations in Fig. 2(a) reveal that every 0.05%/°C reduction in γ could command a 2¢/W, 2.5¢/W, 4¢/W, and 6¢/W increase in module price for total BOS cost of \$0.5/W, \$1/W, \$2/W, and \$4/W, respectively. Calculations in Fig. 2 (b) reveal that every 5 °C reduction in T_{iwoct} could command for 4¢/W, 5¢/W, 8¢/W, and 13¢/W increase in module price for total BOS cost of \$0.5/W, \$1/W, \$2/W, and \$4/W, respectively. Note that each curve in Fig. 2(a) and (b) corresponds to a fixed BOS and fixed LCOE.

In the above calculations, module efficiency was fixed at 16%. Generally, γ varies with open circuit voltage, efficiency or the absorber material. Therefore, an attempt is made to compare the four different promising cell technologies today (c-Si, CdTe, CIGS, and a-Si) by using the model equations and the γ and T_{iwoct} values in Table 1. A 16% efficient c-Si module at \$1/W with γ of −0.45%/°C and T_{iwoct} of 47.3 °C (Phoenix) [6] was used as a reference. Different technologies were compared by calculating module cost that will lead to the same LCOE (Fig. 3). These calculations may help consumers decide which technology to use, which is often a difficult decision due to large number of variables. These results are plotted in Fig. 3(a)–(d). Each figure corresponds to a given BOS, and four technologies are compared for each BOS condition.

Fig. 2. Module cost as a function of (a) temperature coefficient (γ) and (b) irradiance weighted operating cell temperature (T_{iwoct}) for various BOS costs with \$1/W 16% efficient c-Si reference module (red circle). Each curve represents a constant LCOE. LCOE was calculated with an assumption of WACC=7.7% without ITC in Phoenix. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
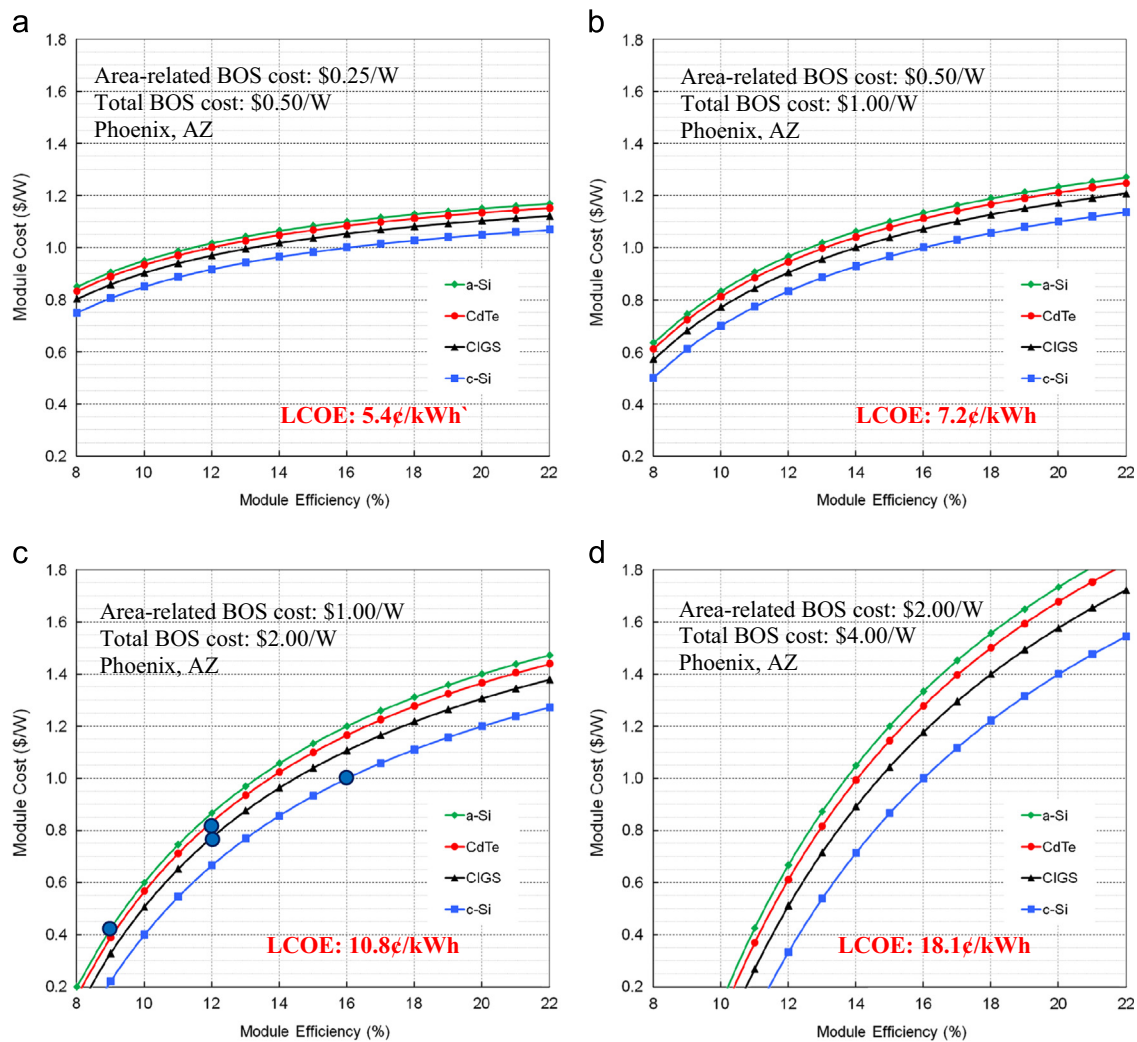
Fig. 3. Module costs for four promising material modules as a function of module efficiency and BOS cost. T_{iwoct} of c-Si module was 47.3 °C, and that of CdTe, CIGS, and a-Si was 45.1 °C, which is equivalent to when module is in Phoenix. LCOE was calculated with an assumption of WACC=7.7% without ITC in Phoenix.

Table 3
Calculated module costs for various BOS costs at Phoenix. $1/W 16% c-Si module ($T_{iwoct}$ =47.3 °C) was used as a reference. Each row provides the same LCOE.

Module cost ($/W)	16% c-Si	12% CdTe	12% CIGS	9% a-Si
C_{Area}: $2/W, C_{BOS}: $4/W	1	0.61	0.51	−0.22
C_{Area}: $1/W, C_{BOS}: $2/W	1	0.83	0.77	0.42
C_{Area}: $0.5/W, C_{BOS}: $1/W	1	0.94	0.90	0.74
C_{Area}: $0.25/W, C_{BOS}: $0.5/W	1	1.00	0.97	0.91

All four curves in each figure correspond to a fixed LCOE. Fig. 3 (c) shows that when area-related BOS cost is $1/W with total BOS cost of $2/W [5], a 12% CIGS module at $0.77/W, 12% CdTe module at $0.83/W, 9% a-Si module at $0.42/W, and 16% c-Si module at $1/W are equivalent and provide same LCOE (Table 3) in Phoenix. Fig. 3 shows a comparison of four technologies for four different BOS conditions ranging from $0.5/W to $4/W and a wide range of module efficiency and cost. This may help a customer to decide which technology to select.

Change in geographical location generally involves change in solar irradiation and corresponding T_{iwoct}. For example, going from Phoenix, AZ to Boston, MA results in a decrease in average solar irradiation from 2256 kW h/m²/yr to 1544 kW h/m²/yr [11] and a decrease in T_{iwoct} from 47.3 °C to 27.3 °C [6]. Lower solar irradiation

hurts the LCOE, but lower T_{iwoct} increases energy production and reduces LCOE. Therefore, we repeated the above calculations for Boston area with reduced T_{iwoct} (Table 1). Fig. 4(a)–(d) shows the module cost vs. efficiency curves for C-Si, CIGS, CdTe, and a-Si modules that will provide same LCOE in Boston for four different BOS conditions. In Fig. 4, all four curves tend to merge indicating that premium due to γ for thin film modules shrinks in lower T_{iwoct} region like Boston. For example, Figs. 3 and 4 show that for $1/W area-related BOS cost, 12% efficient CdTe module can be sold at $0.83/W to compete with 16% Si reference module at $1/W in Phoenix. However, this price drops to only $0.70/W in Boston (Fig. 4) because γ and T_{iwoct} premiums shrink significantly in colder climate. Calculated module costs for different technology PV modules with representative efficiencies in Boston are summarized in Table 4.

Thus, the simple analytical model and equations developed in this paper can quickly quantify equivalent module cost using a simple spread sheet model without running extensive modeling program like SAM [12] to compare various modules with varying γ, T_{iwoct}, efficiency, and cost in different geographical locations with varying BOS and operating temperatures. In order to validate the model and methodology, these results were validated by SAM to ensure that they lead to the same LCOE. Table 5 presents LCOE calculations with varying γ, T_{iwoct}, efficiency, and cost in Fig. 3(d), and it all really provides LCOE of 18.1¢/kW h.
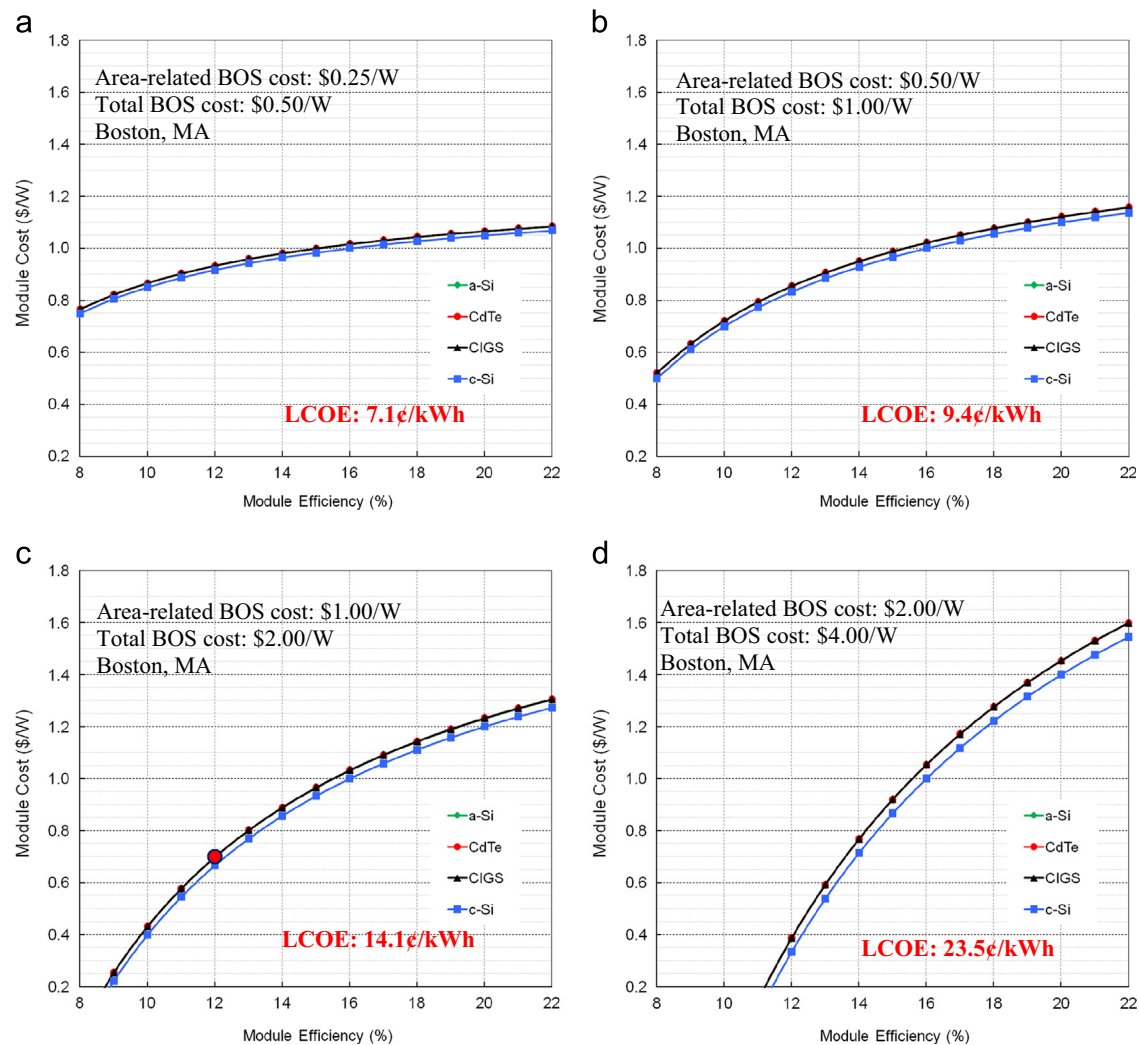
Fig. 4. Module costs for four promising material modules as a function of module efficiency and BOS cost. T_{iwoct} of c-Si module was 27.3 °C, and that of CdTe, CIGS, and a-Si was 24.9 °C, which is equivalent to when module is in Boston. LCOE was calculated with an assumption of WACC = 7.7% without ITC in Boston.

Table 4
Calculated module costs for various BOS costs at Boston. $1/W 16% c-Si module ($T_{iwoct}$ = 27.3 °C) was used as a reference. Each row provides the same LCOE.

Module cost ($/W)	16% c-Si	12% CdTe	12% CIGS	9% a-Si
C_{Area}: $2/W, C_{BOS}: $4/W	1	0.39	0.39	−0.50
C_{Area}: $1/W, C_{BOS}: $2/W	1	0.70	0.70	0.25
C_{Area}: $0.5/W, C_{BOS}: $1/W	1	0.85	0.85	0.63
C_{Area}: $0.25/W, C_{BOS}: $0.5/W	1	0.93	0.93	0.82

Table 5
Verification of analytical equation through the elaborate PV system analysis program, SAM by calculating LCOE (¢/kW h).

Module efficiency (%)	c-Si	CdTe	CIGS	a-Si
11	18.08	18.08	18.07	18.08
12	18.08	18.07	18.07	18.08
13	18.09	18.09	18.08	18.06
14	18.07	18.07	18.06	18.07
15	18.10	18.06	18.09	18.07
16	18.09	18.08	18.08	18.05
17	18.10	18.09	18.08	18.06
18	18.08	18.07	18.07	18.08
19	18.10	18.06	18.06	18.07
20	18.09	18.08	18.08	18.05
21	18.10	18.06	18.06	18.07
22	18.10	18.06	18.06	18.07

4. Conclusions

Analytical equations were developed and used to quantify the equivalent module cost and the associated premium for module efficiency, γ, and T_{iwoct}. The analytical equations can be easily programmed in an excel spread sheet to provide quick and accurate assessment of a new module cost that can lead to same installed system cost and LCOE as a reference module. Application of these analytical equations is shown by first calculating module cost for the same technology but different efficiency (fixed γ and T_{iwoct}) and then extending it to different materials and technologies (crystalline Si and thin films). For example, it is shown that $1/W 16% efficient c-Si module is equivalent to $1.11/W 18% efficient c-Si module in terms of providing same installed system cost and LCOE. In addition, it is shown that $1/W 16% c-Si module is also equivalent to $0.83/W 12% CdTe, $0.77/W 12% CIGS, and $0.42/W 9% a-Si module in a hot climate like Phoenix resulting in the same LCOE. Finally, it is shown quantitatively that the benefit of lower temperature coefficient of thin films is significantly reduced in lower temperature climate. For example, in order for 12% CdTe module to compete with 16% c-Si module in Boston, its price needs to drop from $0.83/W to $0.70/W.

References

[1] Solar Energy Technologies Program: Multi-Year Program Plan 2007–2011, U.S. Department of Energy, 2007.

[2] SunShot Vision Study, U.S. Department of Energy, 2012.

[3] Price, S., 2008 Solar Technologies Market Report, 2010.

[4] Barbose, G., Tracking the Sun III; The Installed Cost of Photovoltaics in the United States from 1998–2009, 2011.

[5] Goodrich A, James T, Woodhouse M. Residential, commercial, and utility-scale photovoltaic (PV) system prices in the United States: current drivers and cost-reduction opportunities. National Renewable Energy Laboratory; 2012 (Technical report).

[6] Ristow AH. Numerical modeling of uncertainty and variability in the technology, manufacturing, and economics of crystalline silicon photovoltaics Thesis. Atlanta, GA, USA: Georgia Institute of Technology; 2008.

[7] Green MA. Solar cells: operating principles, technology and system applications. Kensington, NSW: The University of New South Wales; 1998.

[8] Luque A, Hegedus S. Handbook of photovoltaic science and engineering John Wiley & Sons, Chichester, West Sussex, United Kingdom. 2010.

[9] Deng X, Schiff EA. Amorphous silicon-based solar cells,. Handbook of Photovoltaic Science and Engineering. 2003; 505–65.

[10] D. L. King, J. A. Kratochvil, and W. E. Boyson, Photovoltaic array performance model: United States Department of Energy, 2004.

[11] PVWatts.(http://pvwatts.nrel.gov/index.php), 2014 .

[12] Gilman P, Laboratory NR E, Laboratories SN. Solar advisor model user guide for version 2.0. Golden, CO, USA: National Renewable Energy Laboratory; 2008.